Project Sekwa: A Variable Stability, Blended-Wing-Body, Research UAV

B.A. Broughton and R. Heise
Council for Scientific and Industrial Research
Pretoria, South Africa

D. Blaauw
Stellenbosch University
Stellenbosch, South Africa

ABSTRACT

The Council for Scientific and Industrial Research (CSIR) in cooperation with the Stellenbosch University initiated a research project to investigate and demonstrate a number of challenges related to the aerodynamics and handling characteristics of flying wing and Blended-Wing-Body (BWB) platforms. The main objective of the project was to investigate the advantages and pitfalls of relaxing the longitudinal stability criteria on a Blended-Wing-Body UAV. The project was also aimed at expanding the current aerodynamic analysis techniques and multi disciplinary optimisation capabilities at the CSIR. The project resulted in the construction of a mini-UAV incorporating a variable stability system for use as a research vehicle and technology demonstrator. The paper will discuss the background and goals of the project, the design process, give a brief overview of the control system and control philosophy, hardware in the loop simulation and the first results of the flight test programme. A parallel paper will discuss in detail the aerodynamic and multi-disciplinary optimisation of the UAV.

NOMENCLATURE

C_D	drag coefficient
C_L	lift coefficient
C_l	local or sectional lift coefficient
C_{m0}	moment coefficient at zero lift
c	chord length
T	time
α_{0L}	zero-lift angle of attack
λ	taper ratio
ω_n	natural frequency
ζ	damping ratio

1.0 BACKGROUND

Blended-wing-bodies have become a popular topic for research due to the promised improvement in fuel efficiency over conventional configurations$^{(1)}$. Although much of the research is aimed at future airliners, such as the X-48B$^{(2)}$, the overall compactness of the configuration makes it ideal for many future UAVs of all sizes and applications. As with many flying wing configurations, one disadvantage of the configuration is that, when designed for a positive static margin, the aircraft tends to require a combination of wing twist and sweep of the wing layout to obtain stability, or the use of a reflexed aerofoil section. Since flaps cannot be used for take-off or landing, the wing loading is usually unreasonably low which impairs the cruise and high speed performance. The need for reflexed aerofoils also limits the types of aerofoils that can be practically used, as well as limiting the obtainable aerofoil efficiency and maximum lift coefficient.

One possible approach to reduce these effects is to relax the longitudinal stability requirement and to use the control system to compensate for the reduced stability. A goal of the Sekwa project was to study the impact of relaxing the longitudinal stability constraint during the design process. The wing would then be designed through a numerical optimisation process for comparison of the predicted performance of the resulting design to that of a conventional stable design. The relaxed stability, however, brings new design challenges for the control system which had to be solved before the UAV could be successfully demonstrated in flight.

For research purposes, further flexibility could be added to the design by incorporating an in-flight variable stability system. The control system for the UAV was designed with this variable stability system in mind as an additional trim-like control effector. Stability could be varied in flight by adjusting the centre of gravity through a mechanism that shifted the avionics and flight batteries forward or rearwards to reposition the airframe centre of gravity as demanded by the flight condition.

Other than BWBs being a current global research topic, the choice of developing a flying wing UAV was made due to its simplicity in construction. At the same time the design concept did pose significant challenges in order to form the basis for a technology demonstrator. The main objective of the Sekwa project, however, was to act as a platform for technology and capability development in South Africa, specifically for the design of future aircraft and unmanned vehicles. The technology drive was thus two pronged: First to develop design tools and methods to optimally design the airframe and second, to develop the capabilities to design complex avionics for the control of unmanned systems. Another driver for the project was to establish cooperation between researchers at the CSIR and universities. The aerodynamic and mechanical design was done by the CSIR’s Aeronautics Systems Competency area, while the avionics development was done by the Electronics Systems Laboratory (ESL) of the Department of Electrical and Electronic Engineering at the Stellenbosch University. The development of the avionics systems specific to the Sekwa project formed the topic of an MSc research project.

2.0 DESIGN PROCESS

In order to obtain maximum advantage of the blended-wing-body configuration, a mathematical optimisation approach was implemented in the design process. The objective of the optimisation process was to minimise the drag of the configuration at the target cruise speed of the design while maintaining selected off-design characteristics. Constraints consisted of a combination of natural lateral flying quality requirements, longitudinal flying quality requirements limited by the control system capability, structural requirements and practical geometric constraints.

2.1 Initial Design

The initial phase of the project consisted of developing a user requirement specification which established some of the overall

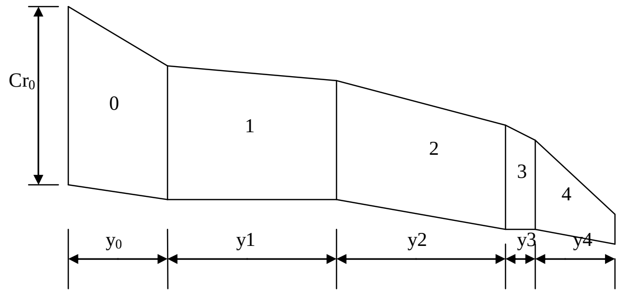


Figure 1. Wing parameterisation

constraints and performance targets of the design. The span of the vehicle was fixed at 1.7 metres to allow the airframe to be tested full scale in the 2 metre open section wind tunnel at the CSIR or in the 5’x8’ low speed wind tunnel. To allow for sufficient time to perform useful flight test analyses during a typical test flight, an endurance of 60 minutes was required for the aircraft. The UAV was to be electrically powered and the estimated mass for the Li-Po batteries was approximately 600g. A total take-off mass of 3.2kg was established based on a similarly sized conventional UAV developed at the CSIR, which would allow for useful performance comparisons. The wing area was calculated based on a landing speed of 11.5m/s with a $C_L = 1.1$. Take-off and landing would be conventional from a model aeroplane runway using a retractable landing gear to reduce drag in flight.

Following the initial design definition, the design of the airframe proceeded in two parts: First the planform of the airframe was defined with the aid of numerical optimisation techniques and then the aerofoils were optimised, also using numerical optimisation.

2.2 Planform Optimisation

The overall objective function for the planform optimisation was minimising the total drag of the flying wing, but with a focus on the induced drag in this phase. The vortex-lattice code AVL was used to calculate the candidate design aerodynamic coefficients and stability derivatives, while various algorithms from a commercial optimisation package was used for the optimisation process. A custom code was developed to interface between AVL and the optimisers while defining the geometry and estimating the mass inertias required for the stability analysis.

The geometry of the airframe was to be a blended-wing-body where the fuselage is represented by a thickening of the wing section and local increase in the chord. The wing was parameterised by dividing it into five panels, as shown in Figure 1. Panel 0 represented the centre “fuselage” section, panels 1 and 2 represented inner and outer wing sections, Panel 3 was a small transition section and Panel 4 would typically develop into a winglet during the design process. Panels 1 and 2 contained the elevon control surfaces, while panel 4 contained the rudder control surface. The relative lengths of each panel were constant values during the design process, but their absolute values were adjusted in order to match the total wing span constraint regardless of the dihedral of individual panels. The root chord was fixed at 520 mm – this distance represented the fuselage length and was independently calculated to ensure that the fuselage length and width would be sufficient to enclose the avionic equipment. The parameters that could be specified by the optimiser for each panel were the following:

- Taper ratio (λ)
- Twist
- Dihedral
- Leading edge sweep
- Aerofoil C_{m0} and α_{0L} values

In order to match the specified wing area, the taper ratio of Panel 0 (the fuselage) was automatically calculated by the code to comply with the specification.

Table 1
Flying Qualities Constraints

Longitudinal unstable real root	< 1 rad/s
Spiral Mode	$T_2 > 12s$
Roll Mode	$T_1 < 1s$
Dutch roll frequency and damping	$\omega_{n,dr} > 1$ rad/s, $\zeta_{dr} > 0.1$
Other constraints	
At Stall: $C_{L\ aircraft} = 1.1$	(C_l outboard) < (0.8 * C_l inboard)
At Cruise:	-1 deg < elevon deflection < 1 deg

Table 2
Geometric Constraints

All panel taper ratios	<= 1.0
Panel 0 and 3 LE sweep	< 60 deg
Panels 1,2, and 4 LE sweep	< 30 deg

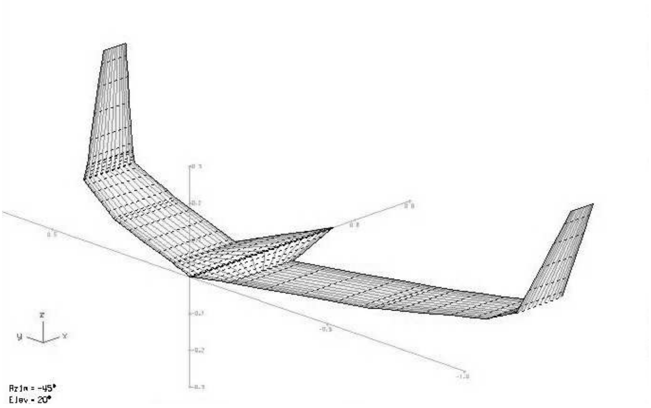


Figure 2. Vortex lattice model after completion of planform optimisation

The objective function was based on an estimate of total drag, using a constant zero-lift drag coefficient adjusted to account for varying wetted areas due to, for example, the winglets. The major effort of the optimiser was therefore to minimise induced drag. The drag was minimized by the optimiser subject to the flying qualities constraints listed in Table 1, while Table 2 lists the geometric constraints enforced on the design. A combination of genetic algorithms and gradient based methods were used for the optimisation. The final planform is shown in Figure 2.

2.3 Aerofoil Optimisation

The optimisation of the aerofoils focused on a wider operating range than just the cruise condition as was the case for the planform optimisation. The objective function for the aerofoils was a combination of the drag coefficients at max speed, cruise speed and loiter speed, and expressed as follows:

$$F = 3C_d|_{\text{cruise}} + C_d|_{\text{max speed}} + C_d|_{\text{loiter}}$$

The constraints for the aerofoil optimisation were the C_{m0} and α_{0L} values from the plan-form optimisation and the requirement that the aerofoil does not stall at the local C_l experienced when the airframe is near the total stall lift coefficient. Additional geometric constraints were added, such as the internal volume required for the moveable avionics and a finite thickness trailing edge of 0.8mm. A family of eight aerofoil sections were optimised individually.

During the optimisation process the candidate aerofoil was again generated using PROFOIL(3) , an inverse aerofoil design code, and the optimiser would adjust the pressure distribution rather than the geometry directly. The analysis of the candidate aerofoil was done using XFOIL, which automatically adjusted the solver parameters to increase the likelihood of convergence. Flap and elevon deflections were also simulated as required. If $C_{l,max}$ of the candidate aerofoil was less than the required $C_{L,max}$, a penalty

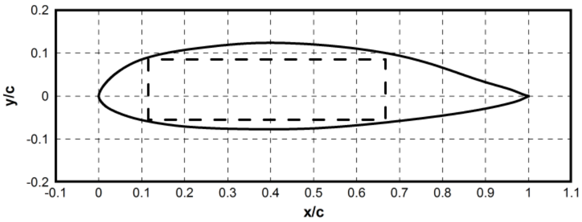


Figure 3. Optimised root aerofoil section showing volume constraint for avionics box

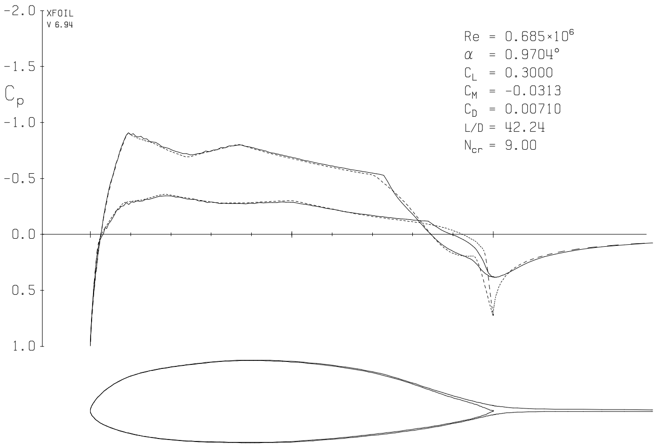


Figure 4. Pressure distribution over the optimised root aerofoil in cruise

function was added. Finally, the depth of the internal volume was calculated when required.

A representative example can be seen in Figure 3, which shows the resulting optimised aerofoil at the root. This is the section containing the avionics tray, outlined by the dashed box in the figure. Figure 4 shows the corresponding pressure distribution for this aerofoil at the local cruise lift coefficient.

3.0 CONTROL SYSTEM

The purpose of the control system was to augment the natural stability of the aircraft such that the nominal static stability could be restored within a range of centre of gravity positions. Additionally the control system was designed to regulate motion variables for autonomous flight.

The control strategy was to implement a closed form high bandwidth inner-loop controller capable of stabilizing the aircraft under various static stability margins. Airspeed, climb rate and altitude controllers were designed to then enable the autopilot to manoeuvre the aircraft longitudinally. Conventional lateral controllers were designed in a successive loop closure fashion. These included a Dutch roll damper as well as turn rate, heading and cross track error controllers. Path planning and cross track error algorithms were implemented to make autonomous waypoint navigation possible.

Finally, two low bandwidth controllers were designed to regulate the centre of gravity position in flight. The first controller allowed the centre of gravity position to be commanded directly while the second regulated the centre of gravity such that a desired average trim elevon position was realised. The reason for the elevon position controller was to allow for an optimal elevon position command that is in line with the optimised aerodynamic configuration; the centre of gravity will then be moved to a position to trim the aircraft.

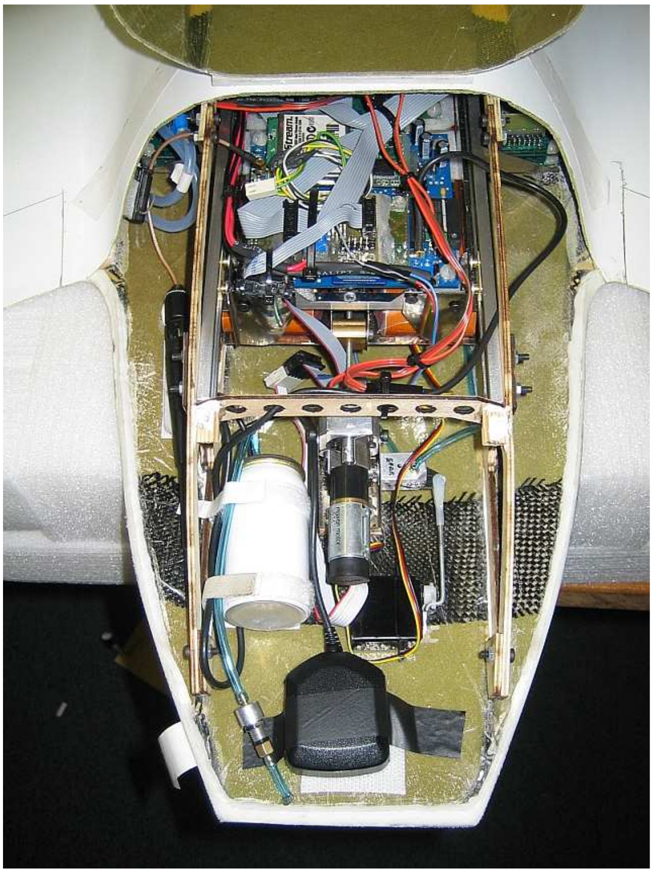


Figure 5. The avionics as installed in Sekwa

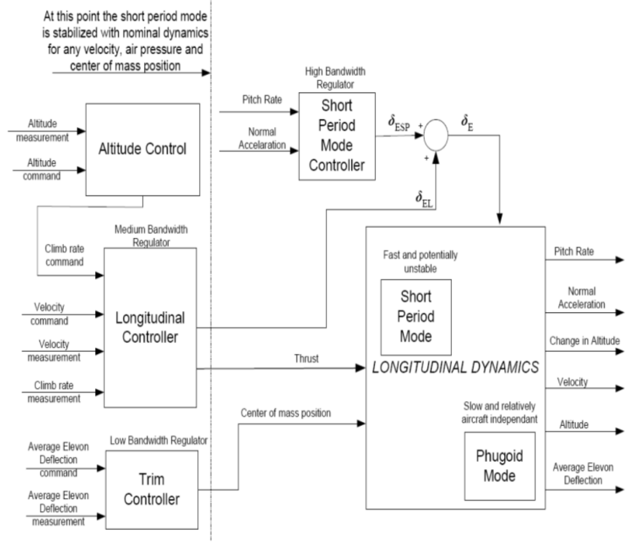


Figure 6. Longitudinal controller block diagram

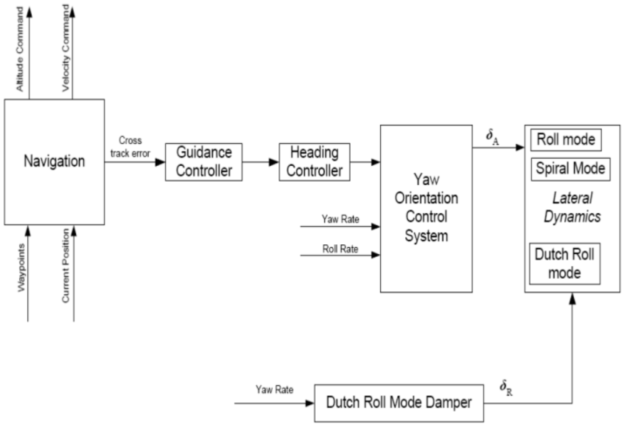


Figure 7. Lateral controller block diagram

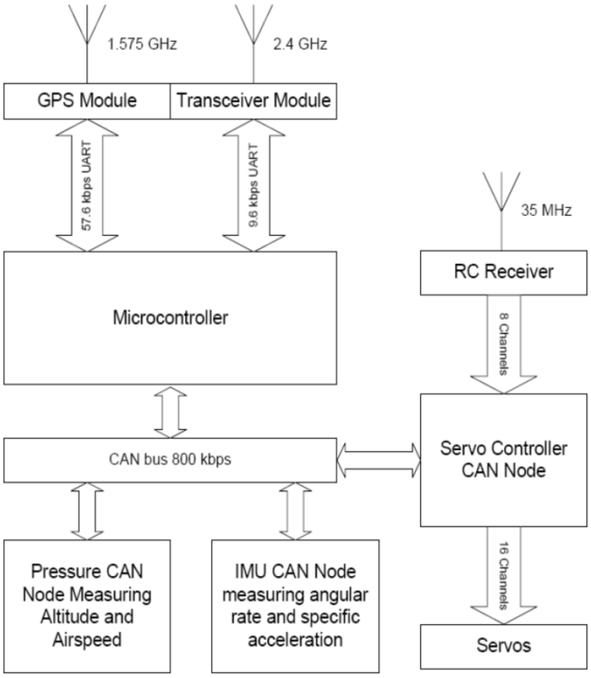
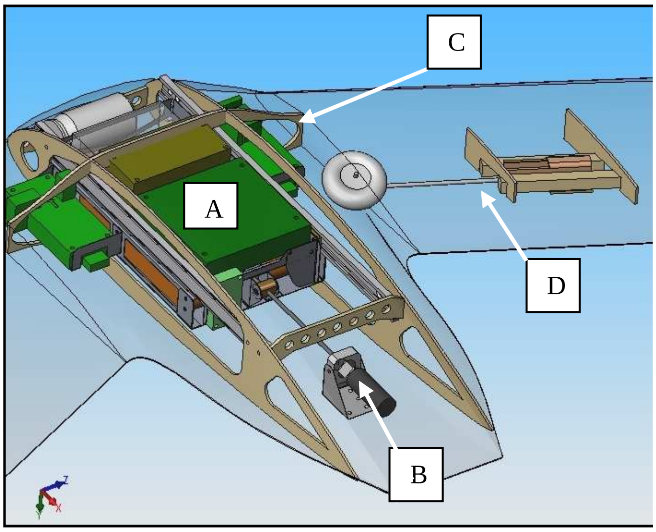


Figure 8. Schematic of the avionic structure



Legend
A: Avionics tray
B: Screw jack mechanism
C: Main spar carry-through web
D: Main gear assembly

Figure 9. CAD model of the avionics tray and central structure

All of the controllers were designed to be computationally inexpensive and could therefore be implemented on small cost-effective embedded microcontrollers. Performing all autopilot functions and calculations on-board the aircraft implied that the aircraft would not be restricted to flying within communications range of the ground station. The avionics were capable of Hardware in the Loop (HIL) simulation which greatly reduced the risk of autopilot errors during flight tests. The HIL simulation included disturbances such as sensor noise, sensor drift and atmospheric conditions such as wind gusts. Figure 5 shows a photograph of the control system as installed in the UAV. Figures 6 and 7 provide a block diagram overview of respectively the longitudinal and lateral control systems.

The avionics were based on the existing avionics developed by the Stellenbosch University. The package consisted of a Microcontroller, radio Frequency Communication Module, GPS Module, Inertial Measurement Unit Module, Pressure node and a Servo controller. Figure 8 shows a schematic block diagram of the avionics.

4.0 DETAIL DESIGN AND CONSTRUCTION

Once the planform and aerofoil optimisation was complete, the design team proceeded with the detail design of the interior structure and avionics tray. Due to the integrated nature of the control system / airframe combination, the two design groups had to be carefully coordinated despite their physical separation (the control system group was situated at Stellenbosch University and the airframe group at the CSIR in Pretoria).

The biggest challenge in the design proved to be the fitment of the moveable avionics tray (item A in Figure 9). At the time of the aerofoil optimisation only estimates of the avionic PCB volumes were available, and thus careful planning was required in the design of the avionics tray to still attain the full 92 mm travel of the avionics tray. The tray was constructed from 0.5 mm stainless steel sheet and mounted on aluminium rails. A screw-jack mechanism was designed to traverse the tray (item B in Figure 9).

Due to the requirement that the tray had to be able to traverse a substantial distance within the airframe, no solid carry-through main spar could be installed in the aircraft. For this the spar cap was thickened in the centre section around the avionics tray and only a small plywood web (item C in Figure 9) could be bonded to the spar cap. This web split outboard of the tray to carry the wing load around the internal volume for the tray. The internal ribs and frame onto which the tray assembly and landing rear was mounted was constructed from laser-cut plywood and spruce strips. These assembles were then in turn sandwiched and bonded between the upper and lower fuselage/wing skins.

Composite technology was used for the construction of the airframe wing, the skin being made up of a Glass/Kevlar/Balsa/HexCell foam sandwich, with the main spar and D-box re-enforcement being from carbon. The composite lay-ups were moulded in CNC manufactured moulds. Once the composite skins were vacuum bagged and cured, the mould halves were joined to bond the top and bottom skins together. Only two mould halves were required for this airframe: one mould for the top surface and another for the bottom surface. As a comparison, a UAV of conventional configuration previously developed at the CSIR of similar size required the manufacture of 14 moulds, thus its machining and construction costs were significantly higher than those of the BWB configuration. High quality R/C servos were used as control surface actuators, while pneumatic actuators were used for retraction of the undercarriage (item D in Figure 9).

5.0 INTEGRATION

The first Sekwa airframe built served the purpose of an “Ironbird”, in other words an airframe that served as a prototype for the construction and for the integration of the avionics. This airframe was sent to the Stellenbosch University for the initial avionics integration and HIL simulations.

Once the avionics were fully functional and integrated, the avionics were removed again for installation in the second Sekwa airframe. In the meantime the Ironbird was converted into R/C Sekwa, a purely radio controlled and simplified airframe that served for initial evaluation of the flying qualities of the aircraft in its stable configuration. The aircraft was given a fixed undercarriage and ballasted to 3.2kg at max forward centre of gravity for this purpose.

The second Sekwa airframe was intended to be the fully functional aircraft on which the actual avionics could be evaluated. Some changes were made to the structure and placement of components based on lessons learned during construction of the ironbird and R/C Sekwa aircraft. The new airframe also had the pneumatically operated retractable undercarriage installed. These changes resulted in a large centre of gravity shift compared to the previous airframe, which necessitated conversion to a tractor configuration in order to balance the airframe correctly without adding additional ballast.

Figure 10. R/C Sekwa in pusher configuration

Figure 11. Sekwa in tractor configuration

This could be done relatively easily due to the motor being housed in a nacelle that did not form an integral part of the fuselage moulding, but the change would require a considerable amount of analysis due to the destabilizing power effects in this configuration as compared to a pusher configuration.

6.0 FLIGHT TESTING

Flight testing up to the time of writing was performed in two stages. First, a radio-controlled version of the UAV was used to evaluate the natural flying qualities of the UAV with the centre of gravity in the most stable location. An off-the-shelf model aeroplane airframe was used to evaluate the control system separately. Final flight testing of the combined system still had to be completed at the time of writing.

6.1 R/C Sekwa

The R/C version of Sekwa (Figure 10) was an unsophisticated prototype of the design used for initial qualitative flight evaluation work. These flight tests included the evaluation of the following characteristics:

- Control system sensitivity
- Climb and descent performance
- Trim settings
- Stall characteristics
- Trim changes with power changes
- Longitudinal static stability
- Lateral-directional stability
- Dutch rolls
- Spiral divergence

The R/C flight tests were performed with a stable static margin and demonstrated excellent longitudinal and lateral flying qualities, with a few minor exceptions. The forward centre of gravity, as compared to the optimal design centre of gravity location, necessitated a considerable amount of nose-up elevon trim during flight. The need for this trim would disappear as the control system starts to move the centre of gravity location backwards. The aircraft did have a slight Dutch roll tendency (as predicted) and the rudders were not very effective although more than adequate for this type of airframe. The aircraft displayed a slowly divergent spiral mode, but this was easily controllable. Unfortunately, during early testing it was discovered that accelerated stalls would result in a spin which seems to be unrecoverable within a reasonable height. Although this resulted in damage to the airframe, the low descent rate due to the flatness of the spin limited the extent of the damage and the airframe was easily repairable.

Performance was good, even with the additional drag of the fixed landing gear and the less than optimal centre of gravity location. Equally, the aircraft decelerated quickly due to the extra drag created by the landing gear such that landings should be executed easily. The elevons were shown to be very effective for roll control. Trim changes due to power changes were also small. Due to the result of the unintentional accelerated stall, no further stall testing was performed.

6.2 Sekwa

With the modification of the propulsion system complete (Figure 11), the test flight program for Sekwa commenced. The test objectives for the initial flights were to verify the airframe from a performance, stability and control perspective. Then the control system was to be evaluated for correct functioning, leading into tests to gain data on the performance variations with centre of gravity adjustments. The performance evaluations were similar to the R/C Sekwa tests and the control system test points included the following system evaluations:

- Yaw damper
- Airspeed and climb rate controller
- Altitude controller
- Turn rate controller
- Heading controller
- Autonomous navigation

The first flight attempt for Sekwa showed that the destabilizing effect of a tractor configuration was not sufficiently accounted for and that the required trim changes from the RC Sekwa version were not estimated correctly. Hence the control system could not be tested in full with the Sekwa airframe. The avionic system has however been tested successfully on an off-the-shelf flying wing model aircraft. The stability augmentation worked well with the exception of an oscillation noticed when shifting the centre of gravity far to the rear. This instability did require some re-coding of the avionic software. At the time of writing the more detailed power effects analysis had been completed, a slight adjustment of the centre of gravity scheduling was made and the control system was ready to be re-mated to the Sekwa airframe.

7.0 CONCLUSION

A blended-wing-body research UAV with variable stability was developed as a combined effort between the CSIR and Stellenbosch University in South Africa. The airframe was developed with the extensive use of mathematical optimisation, focusing on the reduction of aerodynamic drag. Both planform and aerofoil geometries were designed with the optimisation process. The software and methodology developed proved to be valuable design tools, which can now readily be applied to future design efforts. The project has therefore succeeded in reaching all its objectives, with the exception of flight testing which was not complete at the time of writing.

A custom stability augmentation and control system was developed for the UAV. The stability augmentation was tested extensively with HIL simulations and has performed satisfactorily. The avionics have also been successfully demonstrated in flight on a flying wing model aircraft. The cooperation between the CSIR and Stellenbosch University in the development of the avionics for Sekwa worked well and paved the way for continued cooperation on a number of research projects.

Flight tests of the aircraft showed that the aircraft can safely be flown by a human pilot as a backup when the centre of gravity is in the forward position. The control system was designed to automatically change the centre of gravity to this configuration in the case of certain failures or when manually selected by the pilot. As is the case for most flying wings, the stability of the aircraft is very sensitive to centre of gravity position. This is actually an advantage for this airframe, as a wide stability band can be tested using fairly small movements of the variable stability system. However, the destabilising effects of the propulsion system need to be understood and analysed in detail and an appropriate compensation needs to be applied to the centre of gravity position to offset these power effects.

To date no successful flight with the stability augmented Sekwa airframe has been completed due to the additional analysis required after changing to the tractor configuration. Analysis has since been completed, and it was demonstrated that a slight adjustment of the centre of gravity range should be sufficient to compensate for the destabilising effect of the configuration change. The next phase of the flight test program is expected to commence before the end of 2008.

REFERENCES

1. LIEBECK, R.H. Design of the Blended-Wing-Body Subsonic Transport, January 2002, AIAA Paper 2002-0002.
2. WILSON, J.R. Flight Test Time for the Blended-Wing-Body, *Aerospace America*, October 2006.
3. SELIG, M.S. AND MAUGHMER, M.D. A Multi-Point Inverse Airfoil Design Method Based on Conformal Mapping, *AIAA Journal*, 1992, **30**, (5), pp 1162-1170.